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First Results from the TOTEM Experiment

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The first physics results from the TOTEM experiment are here reported, concerning the measurements of the total, differential elastic, elastic and inelastic pp cross-section at the LHC energy of $\sqrt{s} = 7$ TeV, obtained using the luminosity measurement from CMS. A preliminary measurement of the forward charged particle η distribution is also shown.

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1 Introduction

The TOTEM experiment [1], sharing with CMS [2] the same interaction point IP5 of the CERN LHC, is one of the six experiments that investigate high energy physics at this new machine. It has been designed for the measurement of the total pp cross-section (σ_{tot}) with a precision down to 1÷2 %, for the study of the nuclear elastic pp differential cross-section ($d\sigma_{el}/dt$) over a wide range of the squared four-momentum transfer $|t| \sim (p\theta)^2$ ($\sim 10^{-3} < |t| < 10\,\mathrm{GeV}^2$) and for the development of a comprehensive physics programme on diffractive dissociation, partially in cooperation with CMS. These studies will allow to distinguish among different models of soft proton interactions, giving a deeper understanding of the proton structure.

Due to the large uncertainties on available high energy data, the theoretical predictions for σ_{tot}, based on fits to existing measurements on pp and $p\overline{p}$ scattering according to different models, are typically in the 90÷130 mb range [3]. The TOTEM measurement of σ_{tot} at the level of 1÷2 % will allow to discriminate among different models. In order to reach such a small error, the measurement will be based on the "luminosity independent method" which, combining the optical theorem with the total rate, gives σ_{tot} (but also the machine luminosity $\mathcal{L}$, useful for calibration purposes) in terms of the total elastic rate, the total inelastic one and the differential elastic cross-section extrapolated to $t = 0$ (optical point) [4]. The uncertainty on this extrapolation depends on the acceptance for protons scattered at small $|t|$ values, hence at small angles. This requires a small beam angular divergence at the IP, which can be achieved in special runs with high β^* machine optics and typically low $\mathcal{L}$ (in order to have a negligible pile up). An approved optics with $\beta^* = 1540$ m is expected to give a σ_{tot} ($\mathcal{L}$) measurement at the level of 1÷2 % (2%), with the systematic uncertainty dominated by the uncertainty on the corrections to trigger losses for low mass Single Diffraction events [4]. The $\beta^* = 90$ m optics, achievable without modifying the standard LHC injection optics and already tested, can allow a preliminary σ_{tot} measurement with a higher systematic uncertainty dominated by the extrapolation to $t = 0$ [4].

Many details of diffractive (due to colour singlet exchange) and non-diffractive (due to colour exchange) inelastic interactions are still poorly understood. At the same time, these processes, with close ties to proton structure and low-energy QCD, represent a big fraction of σ_{tot}. The majority of diffractive events exhibits intact ("leading") protons characterized by their t and fractional momentum loss $\xi \equiv \Delta p/p$. TOTEM is able to measure ξ-, t- and mass-distributions with acceptances depending on the beam optics. Furthermore, the charged particle flow in the forward region is studied in TOTEM, with the aim to provide in particular a significant contribution to the understanding of cosmic ray physics. The existing models give in fact predictions on energy flow, multiplicity and other quantities related to cosmic ray air showers, with significant inconsistencies in the forward region.

The integration of TOTEM with the CMS detector is also foreseen, resulting in the largest acceptance detector ever built at a hadron collider. This will offer the possibility of more detailed studies on inelastic events, including hard diffraction [5].

In order to fulfill its physics programme TOTEM has to cope with the challenge of triggering and recording events in the very forward region with a good acceptance for particles produced at very small angles with respect to the beam. This involves the detection of elastically scattered and diffractive protons at a location very close to the beam, together with efficient forward charged particle detection in inelastic events with losses reduced to few per-cents.

2 Detector Components

The TOTEM experiment includes three detector components located on both sides of the interaction point IP5 (Figure 1): the T1 and T2 inelastic telescopes, embedded inside the forward region of CMS, and the "Roman Pots" (RPs) detectors, placed on the beam-pipe of the outgoing beam in two stations at about 147 m and 220 m from IP5.

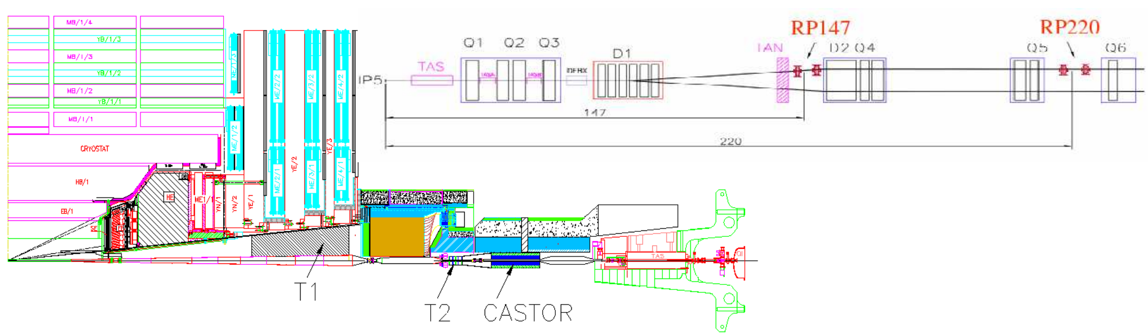

Figure 1: Top: Roman Pots location along the LHC beam-line. Bottom: T1 and T2 location in the forward region of the CMS detector. All TOTEM detectors are located on both sides of IP5.

T1 and T2 are gas detectors providing charged track reconstruction in the $3.1 < |\eta| < 6.5$ range ($\eta = -ln(tan\frac{\theta}{2})$), with a 2π coverage and with a very good efficiency [5]. Their trigger capability, with an acceptance grater than 95% for all inelastic events, allows the measurement of inelastic rates with small losses. At the same time they are used for the reconstruction of the event interaction vertex, allowing to reject background events. Located at $\sim$ 9 m from IP5, each T1 telescope arm covers the range $3.1 < |\eta| < 4.7$ and consists of five planes formed by six trapezoidal "Cathode Strip Chambers" (CSC) [1] (Figure 2, left). These CSCs, with 10 mm thick gas gap and a gas mixture of $Ar/CO_2/CF_4$ (40%/50%/10%), give three measurements of the charged particle coordinates with a spatial resolution of $\sim$ 1 mm: anode wires (pitch

of 3 mm), also giving level-1 trigger information, are parallel to the trapezoid base; cathode strips (pitch of 5 mm) are rotated by $\pm 60^o$ with respect to the wires. The T2 telescope, based on "Gas Electron Multiplier" (GEM) technology [6], extends charged track reconstruction to the range $5.3 < |\eta| < 6.5$ [1]. Each half-arm, located at $\sim$ 13.5 m from IP5, is made by the combination of ten aligned detectors planes having an almost semicircular shape (Figure 2, center). This novel gas detector technology is optimal for the T2 telescope thanks to its good spatial resolution, excellent rate capability and good resistance to radiation. The T2 GEMs are characterized by a triple-GEM structure and a gas mixture of Ar/CO_2 (70%/30%) [1]. The read-out board has two separate layers with different patterns: one with 256x2 concentric circular strips (80 μm wide, pitch of 400 μm), allowing track radial coordinate reconstruction with a resolution of $\sim 100\,\mu$m; the other with a matrix of 24x65 pads (from 2x2 mm^2 to 7x7 mm^2 in size) providing level-1 trigger information and track azimuthal coordinate reconstruction.

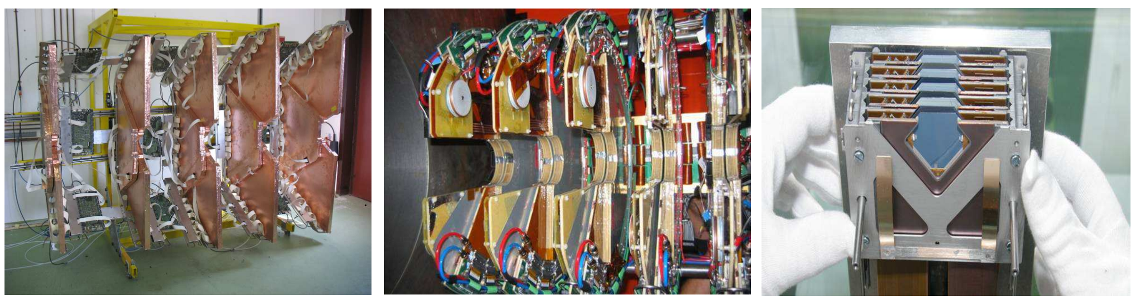

Figure 2: Left (Centre): one half-arm of the T1 (T2) telescope. Right: silicon detectors hosted in one pot.

The RPs are special movable beam-pipe insertions designed to detect "leading" protons with a scattering angle down to few μrad. They host silicon detectors which are moved very close to the beam when it is in stable conditions. Each RP station is composed of two units in order to have a lever harm for a better local track reconstruction and a higher efficiency of trigger selection by track angle. Each unit consists of three pots, two vertical and one horizontal completing the acceptance for diffractively scattered protons. Each pot contains a stack of 10 planes of silicon strip detectors (Figure 2, left). Each plane has 512 strips (pitch of 66 μm), oriented at $+45^o$ (5 planes) or at -45^o (5 planes) w.r.t. the detector edge facing the beam, allowing a single hit resolution of $\sim$ 20 μm. As the detection of protons elastically scattered at angles down to few μrads requires a detector active area as close to the beam as $\sim$ 1 mm, a novel "edgeless planar silicon" detector technology has been developed for TOTEM RPs in order to have an edge dead zone minimized to only $\sim$ 50 μm [7].

The read-out of all TOTEM sub-detectors is based on the digital VFAT chip, specifically designed for TOTEM and characterized by trigger capabilities [4].

3 First Physics Results

TOTEM has performed a first measurement of $d\sigma_{el}/dt$ at $\sqrt{s} = 7$ TeV in the 0.36 $< |t| <$ 2.5 GeV^2 range using data taken in 2010 with the standard optics ($\beta^* =$ 3.5 m) during a dedicated run at low luminosity [8]. A total luminosity of 6.1 nb^{-1} was integrated with the RP detectors approaching the beams as close as 7 times the transverse beam size (σ_b). The background was significantly reduced a the trigger level by requiring collinear hits in a pot in at least three of the five planes for each projection (trigger tracks) on both sides of the IP. Elastic candidates were then selected offline by applying proper cuts in order to reject the background from diffractive events and by requiring a reconstructed track in both projections of the vertical RP units on each side of the IP in a "diagonal" topology: top (bottom) left of IP - bottom (top) right of IP. Dedicated procedures have been performed in order to ensure the precision and the reproducibility of all RP detector planes alignment with respect to each other and to the position of the beam centre, one of the most delicate ad difficult tasks of the experiment. A precise relative alignment (at the 10 μm level) of all three RPs in a unit has been obtained during the measurement by correlating their position via common particle tracks reconstruction in the overlap zone of the horizontal RPs with the vertical ones. The global symmetrical alignment of all the RPs with respect to the beam centre has been obtained (with a precision $\sim$ 50 μm) during a dedicated beam fill by moving them towards the sharp beam edge cut by the beam collimators, until a beam losses spike was observed downstream of the RPs. The final horizontal and vertical alignment has then been achieved from studies on the reconstructed tracks. The horizontal (Θ^*_x) and vertical (Θ^*_y) scattering angles at the IP were deduced from the measurement of the track angle (for Θ^*_x) and of the displacement in y (for Θ^*_y) at the RP stations using the optical functions, which describe the explicit proton path through the LHC magnetic elements as a function of the proton position and scattering angle at the IP. Event selection has been performed by requiring a strict correlation (consistent with the beam divergence at the IP) between the two Θ^*_x (and Θ^*_y) reconstructed on both sides of IP, resulting in a t-resolution of $\delta t = 0.1$ GeV$\sqrt{|t|}$. The detector efficiency and acceptance corrections have been computed from simulation, while bin migration due to resolution and beam divergence effects has been corrected using two independent unfolding procedures based on analytical and on MC methods which gave consistent results. The contribution of background events passing the selection cuts was evaluated from studies on data. The total luminosity associated to the collected data has been derived from the instantaneous luminosity measurement performed by CMS with an uncertainty of 4% [9, 10], integrated over the data taking period and then corrected for trigger and DAQ efficiency effects. Figure 3 (left) shows the measured $d\sigma_{el}/dt$ with the related statistical errors, the one on t given by the beam divergence. The systematic uncertainties, reported as reference only in two points, are dominated in t by optics and alignment, while in

$d\sigma_{el}/dt$ by the uncertainty on the efficiency corrections and the resolution unfolding. For $|t| < 0.47$ GeV^2 the data can be described by an exponential function with slope $B = (23.6 \pm 0.5^{stat} \pm 0.4^{syst})$ GeV^{-2}, which is expected to change at smaller $|t|$ values. The expected diffractive minimum, typically pronounced in pp scattering, is then observed at $|t| = (0.53 \pm 0.01^{stat} \pm 0.01^{syst})$ GeV^2. At higher $|t|$ the $d\sigma_{el}/dt$ can be described by a power law $|t|^{-n}$, with $n = 7.8 \pm 0.3^{stat} \pm 0.1^{syst}$, in the $|t|$-range 1.5 - 2.0 GeV^2. The comparison with the predictions of different available theoretical models shows a partial consistency with the data (slope B, dip position and exponent n at large $|t|$) only for some of them.

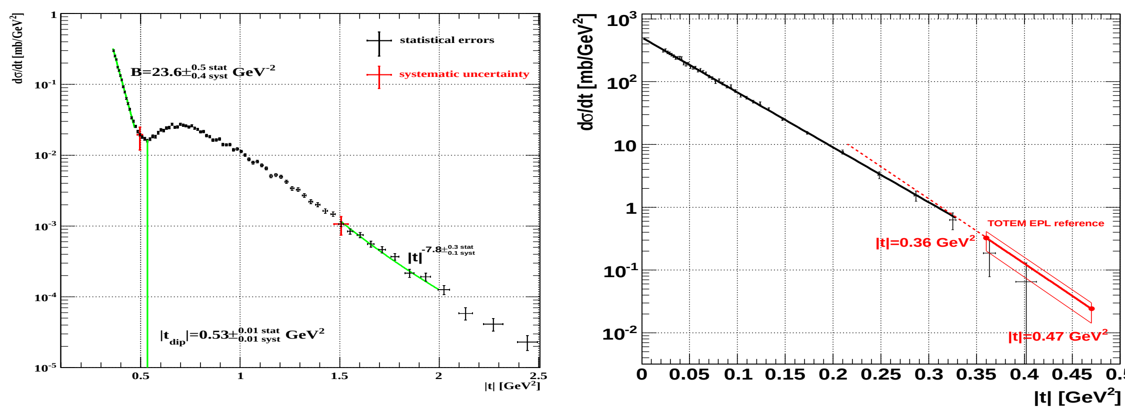

Figure 3: Left: first measurement of $d\sigma_{el}/dt$ with the standard $\beta^* = 3.5$ m LHC optics. Right: extension of the measurement at low $|t|$ with the $\beta^* = 90$ m optics.

Analyzing the data from a short 2011 run with dedicated large β^* optics ($\beta^* = 90$ m) and low luminosity, TOTEM has also measured $d\sigma_{el}/dt$ at low $|t|$ in the $2 \times 10^{-2} < |t| < 0.42$ GeV^2 range [11]. During this special run a total luminosity of 1.65 μb^{-1} was integrated with the RP detectors placed 10 times σ_b from the beam centre, using a loose trigger requiring a track segment in any of the vertical RPs in at least one of the two transverse projections. The analysis strategies were substantially the same as in the previous measurement at larger $|t|$, the luminosity being still provided by the CMS experiment with an uncertainty of 4%. The uncertainty on the $|t|$ scale for this optics was found to vary from 0.8% at low $|t|$ to 2.6% at high $|t|$. The results are reported in Figure 3 (right), were the exponential fit at the lower end of the $|t|$ range of the previous measurement is also shown for comparison, showing a very good agreement between the two measurements performed with different optics. An exponential fit with a slope $B = (20.1 \pm 0.2^{stat} \pm 0.3^{syst})$ GeV^{-2} describes the lowest range of $|t|$ from 0.02 to 0.33 GeV^2. The low $|t|$ value reached with this optics made the exponential extrapolation to $t = 0$ possible, allowing the first measurement of the total pp cross-section at the LHC using the optical theorem, the luminosity

measurement from CMS and the ρ parameter from theoretical predictions [3]. A σ_{tot} of $(98.3 \pm 0.2^{stat} \pm 2.8^{syst})$ mb was obtained, which is in good agreement with the expectation from the overall fit of previously measured data over a large range of energies [3]. The errors on this measurement are dominated by the extrapolation to $t = 0$ and by the luminosity uncertainty. Furthermore, the integration of $d\sigma_{el}/dt$ gave a σ_{el} of $(24.8 \pm 0.2^{stat} \pm 1.2^{syst})$ mb. By combining the σ_{tot} and σ_{el} measurements, a inelastic cross-section (σ_{inel}) of $(73.5 \pm 0.6^{stat}\ {}^{+1.8}_{-1.3}\ {}^{syst})$ mb was inferred, which is in good agreement with the measurements of the ALICE [12], ATLAS [13] and CMS [14] experiments within the quoted errors.

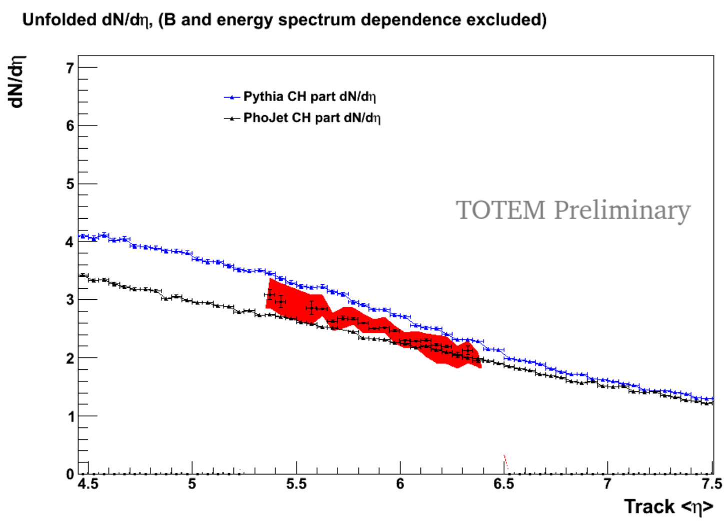

Figure 4: Preliminary measurement of $\frac{dN}{d\eta}$ (black points with statistical error), compared to predictions from Pythia6 (blue triagles) and Phojet (black triangles). The red band represents the combination of the main systematic uncertainties.

A preliminary measurement of the forward charged particle η distribution has also been performed by TOTEM using the data taken in special 2011 runs at low luminosity with an inclusive T2 trigger. Particular effort has been devoted to correct for misalignment biases, found to be dominated by global T2 quarter displacements. The relative alignment between the two quarters of an arm has been obtained using tracks reconstructed in the overlap regions, while the global alignment has been derived by studying the expected symmetry in the track parameters distributions and the position on each T2 plane of the "beam pipe shadow" (very low track efficiency radial zone due to primary particles absorbed by the $\eta \sim 5.54$ beam pipe cone). Secondary track rejection has been derived from data analysis, while primary track efficiency and smearing effects correction have been obtained from MC studies. The results are reported in Figure 4, where the black points show the experimental measurements with their statistical error. The red band represents the sum in quadrature of the

main systematic uncertainties, related to the estimation of the track efficiency and detector alignment corrections and to the subtraction of secondary track contribution. Work is in progress for the determination of the residual systematics related to the MC modeling of the forward particle energy spectrum and to the simulation of the magnetic field effects. These last, less relevant uncertainties, are expected to give an additional contribution at the level of few percent.

4 Summary and Conclusions

The TOTEM detectors have been completely installed and, after a commissioning period, are fully operative. From the analysis of the data taken during dedicated runs at low luminosity with both the standard $\beta^* = 3.5$ m and the high $\beta^* = 90$ m optics, the first (luminosity-dependent) measurements of the total, differential elastic and elastic pp cross-section at the LHC energy of $\sqrt{s} = 7$ TeV have been obtained. The inelastic pp cross-section has also been inferred from the total and elastic ones, which is in good agreement within the errors with the measurements of other LHC experiments (ALICE, ATLAS and CMS). A preliminary measurement of the forward charged particles η distribution has also been performed.

The inclusion of the T1 and T2 inelastic telescopes in the analysis of the data to be taken during a high statistics run with $\beta^* = 90$ m, foreseen in fall 2011, will allow a luminosity-independent measurement of the total pp cross-section and a detailed study of low mass diffraction.

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